Neutrino-deuteron reactions at solar neutrino energies

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In interpreting the SNO experiments, accurate estimates of the νd reaction cross sections are of great importance. In our recent work [1], we have improved our previous calculation by updating some of its inputs and by incorporating the results of a recent effective-field-theoretical calculation. The new cross sections are slightly ($\sim$1 %) larger than the previously reported values. It is reasonable to assign 1% uncertainty to the νd cross sections reported here; this error estimate does *not* include radiative corrections.

1. Introduction

The establishment of the Sudbury Neutrino Observatory (SNO) has greatly increased the necessity of detailed theoretical studies of the neutrino-deuteron (νd) reactions[1–5]. At SNO, neutrino oscillations can be directly tested by measuring the solar electron-neutrino flux using the charged-current (CC) reaction ($\nu_e d \to e^- pp$) and the total solar neutrino flux using the neutral-current (NC) reaction, $\nu_x d \to \nu_x pn$ ($x = e, \mu$ or τ). The recent SNO results[6] have given definitive evidence for neutrino oscillations. To make the best use of the existing and future SNO data, it is highly desirable to further improve the theoretical estimates of the νd cross sections.

A traditional approach for describing nuclear electroweak processes consists in evaluating the contributions of 1-body impulse-approximation (IA) operators and 2-body exchange-current (EXC) operators defined in the Hilbert space of non-relativistic nuclear wave functions, with the EXC terms derived from one-boson exchange diagrams. We refer to this approach as SNPA (standard nuclear physics approach). The calculations of the νd cross sections ($\sigma_{\nu d}$) based on SNPA have been done by several authors [4]; the most recent work due to Nakamura *et al.* shall be referred to as NSGK [2] and NETAL [1].

An alternative approach, effective field theory (EFT), has been applied to the νd reaction by Butler *et al.*(BCK)[5]. The EFT lagrangian used by BCK involves one unknown low-energy constant (LEC), L_{1A}, which BCK adjusted to optimize fit to the $\sigma_{\nu d}$ of NSGK. After this fine-tuning, the results of BCK were found to agree with those of NSGK within 1% over the entire solar-neutrino energy region. Very recently, Ando *et al.* have performed an EFT-motivated calculation of $\sigma_{\nu d}$ [3] using a method called EFT*; in this approach, originally proposed by Park et al.[7], the electroweak transition operators are derived with a cut-off scheme EFT, while the initial and final nuclear wave functions are obtained with the use of a realistic phenomenological NN potential. The EFT* lagrangian contains an unknown LEC, denoted by $\hat{d}^R$, which plays a role similar to L_{1A} in BCK. In EFT*, however, $\hat{d}^R$ can be determined directly from the tritium β-decay rate Γ_t^β, which allows a parameter-free calculation of the νd cross sections.

We give here a concise account of the latest SNPA calculation of the νd reaction carried out in NETAL [1]. The main points of improvement over NSGK are as follows. First, the updated value of the axial coupling constant g_A is used. Secondly, the treatment of the axial-vector exchange current ($\boldsymbol{A}_{\rm EXC}$) is improved. Since the νd reaction in the solar-neutrino energy region is dominated by the Gamow-Teller (GT) transition, $\boldsymbol{A}_{\rm EXC}$ is a crucial ingredient that controls the accuracy of calculated cross sections. Among the various terms in $\boldsymbol{A}_{\rm EXC}$, the Δ-excitation current is the most important one. NETAL uses the Δ-excitation current determined in Ref. [9] to reproduce the experimental value of Γ_t^β. Thirdly, NETAL employs the effective Fermi coupling constant $G_F^\prime$ that includes inner-radiative corrections instead of G_F used in NSGK. Furthermore, the stability of theoretical estimates is investigated by comparing the new SNPA calculation with Ando *et al.*'s EFT* calculation [3].

2. Formalism

The interaction hamiltonian (H_W) for a weak semileptonic process is given by the product of the hadron current (J_λ) and the lepton current (L^λ) as

$$H_W^X = \frac{G_F^X}{\sqrt{2}} \int d\boldsymbol{x}[J_\lambda^X(\boldsymbol{x}) L^\lambda(\boldsymbol{x}) + \text{h. c.}], \tag{1}$$

with X=CC or NC, and $G_F^{CC}(G_F^{NC}) = G_F^\prime V_{ud}(G_F^\prime)$, where $G_F^\prime$ is the weak coupling constant determined from the 0^+-0^+ β-decay rates, and V_{ud} is the K-M matrix element. The hadron current is the sum of the vector (V_λ) and the axial current (A_λ);

$$J_\lambda^{CC}(\boldsymbol{x}) = V_\lambda^+(\boldsymbol{x}) + A_\lambda^+(\boldsymbol{x}) \tag{2}$$

for the CC reaction and

$$J_\lambda^{NC}(\boldsymbol{x}) = (1 - 2\sin^2\theta_W) V_\lambda^3(\boldsymbol{x}) + A_\lambda^3(\boldsymbol{x}) - 2\sin^2\theta_W V_\lambda^s(\boldsymbol{x}) \tag{3}$$

for the NC reaction. Here θ_W is the Weinberg angle. The hadron current consists of the 1-body IA current and the 2-body EXC, whose explicit forms can be found in Ref. [1]. Other details of the calculation including multipole expansion and the cross section formula are given in Ref.[2]. For numerical results, NETAL used the deuteron and the NN scattering wave functions generated with the ANLV18 potential [10].

3. Results and Discussion

The calculated total cross section for the CC reaction ($\sigma_{\nu d}^{CC}$) is shown in Fig.1 as a function of the incident neutrino energy (E_ν). Although the cross section is dominated by the GT transition leading to the final ${}^1S_0$ NN state, the transitions leading to higher partial waves are not totally negligible; they account for 1% and 4% of the reaction rate at $E_\nu \sim 10$ MeV and $E_\nu \sim 20$ MeV, respectively.

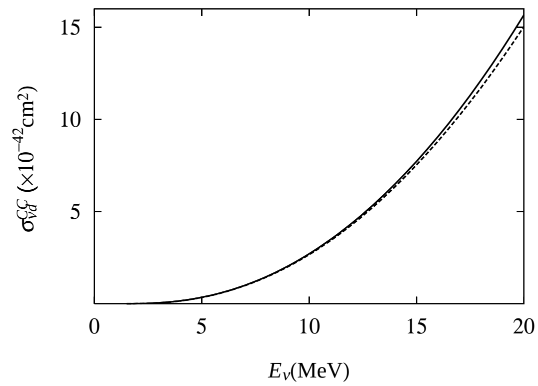

Figure 1. Total cross sections for the CC reaction. The solid- (dotted-) curve includes all ($^1S_0$) partial waves of the final two-nucleon system.

E_ν (MeV)	NETAL	NSGK	normalized
5	1.019	1.050	1.020
10	1.023	1.059	1.024
20	1.029	1.068	1.030

Table 1
Contributions of EXC for the CC reaction. The ratio, $\sigma_{\nu d}^{CC}$(IA+EXC)/$\sigma_{\nu d}^{CC}$(IA), is shown for NETAL (2nd column) and for NSGK (3rd column). The fourth column corresponds to the use of the "normalized" $\boldsymbol{A}_{\rm EXC}^{\rm NSGK}$ explained in the text .

E_ν (MeV)	$\nu_e d \to e^- pp$	$\nu d \to \nu pn$
5	1.003	1.004
10	1.001	1.003
20	0.998	1.001

Table 2
Comparison of SNPA and EFT*. The ratio $\sigma_{\nu d}$(EFT*)/$\sigma_{\nu d}$(SNPA) is shown for the CC and NC reactions.

The ratio $\sigma_{\nu d}^{CC}$(IA+EXC)/$\sigma_{\nu d}^{CC}$(IA) is shown in Table 1 for both NETAL and NSGK. In NETAL, the EXC contribution to $\sigma_{\nu d}^{CC}$ is ~2%, which is ~3% smaller than the NSGK results. The strength of $\boldsymbol{A}_{\rm EXC}^{\rm NSGK}$ was determined by analyzing the $np \to \gamma d$ reaction and assuming a quark-model relation between the axial vector and vector coupling constants for the $N\Delta$ transition. We note, however, that Γ_t^β should give a much more direct constraint on $\boldsymbol{A}_{\rm EXC}$ than $\sigma(np \to d\gamma)$, the latter being governed by the vector current. One way to gauge the sensitivity of $\sigma_{\nu d}$ to different choices of $\boldsymbol{A}_{\rm EXC}$ is to normalize the strength of $\boldsymbol{A}_{\rm EXC}^{\rm NSGK}$ near threshold to reproduce $\boldsymbol{A}_{\rm EXC}^{\rm NETAL}$. With this normalization applied, the difference between the two EXC models is reduced to 0.2%; see the fourth column in Table 1. Thus it is the overall strength of $\boldsymbol{A}_{\rm EXC}$ that controls the low-energy νd reactions; $\sigma_{\nu d}$ is insensitive to the detailed structure of $\boldsymbol{A}_{\rm EXC}$ once EXC is adjusted to reproduce Γ_t^β.

Comparison with an EFT* calculation [3] provides a further test of the reliability of $\sigma_{\nu d}$ obtained in NETAL. It is sufficient to make this comparison for the reaction rate leading to the final $^1S_0$ state. Table 2 shows the ratio $\sigma_{\nu d}$(EFT*)/$\sigma_{\nu d}$(SNPA), from which we can conclude that SNPA and EFT* give identical results within 1% accuracy. This agreement proves the robustness of the theoretical estimates of $\sigma_{\nu d}$ obtained in NETAL.

With the improved inputs as described above, NETAL have obtained $\sigma_{\nu d}$'s that are slightly larger ($\sim$1%) than those of NSGK. The $\sigma_{\nu d}$'s in NETAL are considered to be reliable within 1% accuracy.

Besides the absolute value of $\sigma_{\nu d}$, the ratio $R = \sigma_{\nu d}^{NC}/\sigma_{\nu d}^{CC}$ is an important quantity for SNO experiments. Comparing the R's obtained in NETAL, NSGK and EFT*, we can assign 0.5% accuracy to the calculated R.

The radiative corrections are expected to affect $\sigma_{\nu d}$ at the level of a few per cent. NETAL only took into account a part of the radiative correction incorporated into G_F'; the most recent estimation of the remaining radiative corrections can be found in Ref. [11].

A new experimental value of g_A has been presented at this conference by Abele [12]. The reported value, g_A=1.274, is significantly larger than the current PDG value used by NETAL. We remark, however, that if the calculation of NETAL is repeated with the use of this new value of g_A, the resulting $\sigma_{\nu d}$'s would be essentially unchanged. Since the strength of $\boldsymbol{A}_{\rm EXC}$ in NETAL is determined to reproduce Γ_t^β, an increase in g_A is largely compensated by a decrease in $\boldsymbol{A}_{\rm EXC}$, leaving $\sigma_{\nu d}$'s essentially unaffected.

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